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Final Report
Orbiting Propellant Depot Safety
Volume III: Appendices

Prepared by ADVANCED VEHICLE SYSTEMS DIRECTORATE
Systems Planning Division

20 SEPTEMBER 1971

Prepared for OFFICE OF MANNED SPACE FLIGHT
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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Systems Engineering Operations
THE AEROSPACE CORPORATION

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PREFACE

This study was initiated as Subtask 3, Orbiting Propellant Depot Safety Study of NASA Study C-II, Advanced Missions Safety Studies. Other studies in this series are: (i) Subtask 1, TNT Equivalency Study, Aerospace Report No. ATR-71(7233)-4; and (ii) Subtask 2, Safety Analysis of Parallel versus Series Propellant Loading of the Space Shuttle, Aerospace Report No. ATR-71(7233)-1.

The study was supported by NASA Headquarters and managed by the Advanced Missions Office of the Office of Manned Space Flight. Mr. Herbert Schaefer, the Study Monitor, provided guidance and counsel that significantly aided this effort.

Study results are presented in three volumes; these volumes are summarized as follows:

> Volume I: Management Summary Report presents a brief, concise review of the study content and summarizes the principal conclusions and recommendations.
>
> Volume II: Technical Discussion provides a discussion of the available test data and the data analysis. Details of an analysis of possible vehicle static failure modes and an assessment of their explosive potentials are included. Design and procedural criteria are suggested to minimize the occurrence of an explosive failure.
>
> Volume III: Appendices contains supporting analyses and backup material.

ACKNOWLEDGEMENT

The principal participants in this study of The Aerospace Corporation were:

M. Donabedian	Semimodular/Modular Concept Development and Analysis
R. P. Toutant	Docking/Transfer Interface Concept Development and Analysis
R. R. Wolfe	Study Manager and Director Operations Office Advanced Vehicle Systems Directorate
H. H. Yoshikawa	Integral Concept Development and Analysis

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SELECTION OF ORBITING PROPELLANT DEPOT PROPELLANT TRANSFER SUBSYSTEMS

A.1 GENERAL

There are three basic requirements to be satisfied when considering the flow transfer of propellants at the Orbiting Propellant Depot (OPD). These are: (i) a method for propellant settling (ullage control); (ii) a means of pressurization; and (iii) the propellant transfer technique. This appendix discusses the selection of the required subsystems for the study baseline system; contractor data were used wherever possible in selecting subsystems for the study baseline configurations.

A.2 ULLAGE CONTROL

Four methods of ullage control were considered: (i) linear acceleration, (ii) rotational acceleration, (iii) dielectrophoresis, and (iv) capillary retention. The basic characteristics of the methods are described and evaluated in the following paragraphs and are summarized in Tables A-1 and A-2.

A.2.1 Description of Ullage Control Subsystems

A.2.1.1 Linear Acceleration

In the linear acceleration method, vehicle thrust is applied along an axis of the OPD for the entire duration of the propellant transfer; acceleration is generally provided in the direction normal to the orbit plane and is relatively small, on the order of approximately 10^{-4} g's. An attractive feature of the linear acceleration method is that the OPD and the resupply OV move as an integral system and there is no relative motion or movement within OPD/OV combination itself. The OPD must be accelerated during the entire transfer method.

Table A-1. Ullage Control System Characteristics

Method		Characteristics
Linear Acceleration	1	Thrust applied along longitudinal axis (normal to orbit plane)
	2	Acceleration applied for entire transfer period
	3	Thrust period equal to integer orbit time to maintain orbit
	4	SPS Penalty
Rotational Acceleration 1	1	OPD rotated about pitch or yaw axis
	2	Torque applied only to achieve desired rotational level
	3	Low SPS penalty
Rotational Acceleration 2	1	Depot rotated about the longitudinal (roll) axis
	2	Torque applied only to achieve desired rotational level
	3	Low SPS penalty
Dielectrophoresis	1	Dielectric fluid orientation achieved by imposing electromagnetic field
	2	Power penalty
	3	Difficult to test large systems
Capillary	1	Surface tension forces dominant in low-g environment
	2	Liquid contained by capillaries, wicks, screens, etc.
	3	Large residual penalty
	4	Difficult to test large systems

Table A-2. Comparison-Ullage Control Systems

Ullage Control Mode	Major Advantages	Major Disadvantages
Linear Acceleration	1. Lightest weight system for optimum LH_2 propellant transfer time. 2. Readily adaptable and suited to pump transfer mode; turbine thrust recovery supplies sufficient ullage control. 3. Active and positive means of ullage control. 4. Propellant residuals minimized by baffling.	1. Creates orbital perturbations in tanking orbit unless special orientation is accomplished; can be minimized by placing vehicle normal to orbital plane and transferring propellants in one orbital period.
Rotational Acceleration	1. Minimizes propellant consumption to achieve a specific normal acceleration for propellant positioning; begins to pay off in longer propellant transfer times (< 5 hr). 2. Propellant transfer time not limited to multiples of orbital period. 3. Minimizes potential orbital perturbations.	1. Heavier system weight due to transferring propellant from far end of tanker. System pressure drop increases, which increases turbopump drive propellants or higher pressurant requirements and residual gas weight for direct pressure propellant transfer. 2. Complex transfer operations due to continual shifting of cg and mass moment of inertia; under some conditions, special venting from center of tank in OPD required. 3. Potential guidance and communication problems created by vehicle tumble.
Rotational Acceleration (about roll axis)	1. Minimizes propellants for ullage control (only with baffles). 2. Minimizes orbital perturbations. 3. High normal accelerations easily obtained by roll nozzles to increase Bond Number and depress level of suction dip.	1. High propellant residuals possible; must increase normal acceleration in effort to reduce residuals. 2. Baffling required to suppress suction dip residuals; complex tank side sump design. 3. Rotational baffles required for rotation of fluid.
Dielectrophoresis	1. Completely passive ullage control mode. 2. No orbital perturbations.	1. Heavy system due to electrodes, attachments, and power supply. 2. Designed for a specific transfer time; shorter times cannot be accomplished; not versatile. 3. New and untried concept; would require considerable development time and funds.
Capillary Systems	1. Completely passive ullage control mode. 2. No orbital perturbations.	1. System limited in external accelerations capabilities. 2. Concepts not tested or demonstrated to ensure propellant orientation. 3. Seriously influenced by slosh and heat leak to propellant; can alter liquid/gas equilibrium configurations. 4. No positive mode of ullage control.

A.2.1.2 Rotational Acceleration

Two modes of rotational acceleration were considered for ullage control; (i) rotation about the pitch or yaw axis, and (ii) rotation about the roll axis.

In the pitch/yaw rotation method, the entire OPD/user OV combination is rotated around either the pitch or the yaw axis. OPD rotational thrust would be required only to achieve the desired rotational rate, and thereafter thrust would not be required. However, stabilization around the rotational axis must still be provided.

In the roll rotation acceleration method, the entire OPD/user OV combination rotates around the roll axis. This is similar to the pitch/yaw rotation method; however, the OPD itself is in a more stable attitude when rotating around the roll axis. Rotational thrust is applied only to achieve the desired rotational level in this method also.

A.2.1.3 Dielectrophoresis

The dielectrophoretic ullage control utilizes the dielectric characteristics of either of the cryogenic propellants in order to orient the liquid and vapor. An electromagnetic field is imposed in the tank and, because of the differences in dielectric characteristics between the liquid and the vapor, liquid and vapor separation is achieved.

A.2.1.4 Capillary Retention

The fourth method of ullage control considered was a capillary retention device. Because of the low-g environment in orbit, surface tension forces dominate and liquid can be oriented within a capillary or wick structure.

A.2.2 Evaluation of Methods

A.2.2.1 Linear Acceleration

Linear acceleration provides the lightest weight ullage control system for optimum LH_2 transfer time; it is well suited for pump transfer and also is an active and positive means of ullage control. The vapor pullthrough can be delayed and propellant residuals minimized by proper baffling of the OPD tank. A major disadvantage with the linear acceleration method is that the acceleration imposes a perturbation on the orbit of the OPD. This problem can be partially alleviated by using low levels of acceleration (approximately 10^{-4}g) and by accelerating the vehicle in the direction normal to the orbital plane for integral numbers of orbits.

A.2.2.2 Rotational Acceleration

Rotational acceleration utilizes small quantities of thrust propellant, and consequently, is attractive for long-duration propellant transfers (five hours). Propellant transfer time need not be limited to multiples of orbital periods, and also orbital perturbations can be minimized. This method however may necessitate long transfer lines because of the propellant locating itself in the extreme ends of the OPD. In addition, guidance and communications problems may be aggrevated because of the continual rotation of the vehicle and the continual shifting of its cg and its mass moment of inertia. The roll acceleration method is quite similar to the pitch/yaw acceleration method. However, this method is more stable than the pitch/yaw method because the rotation is along a major axis.

A.2.2.3 Dielectrophoresis

The primary feature of the dielectrophoretic method of ullage control is that the system is completely passive and there are no orbital perturbations imposed on the OPD. However, it is a heavy system because of the necessary electrodes, attachments, and power requirements; furthermore, no system has been tested or developed for the large scale OPD which is under consideration.

A.2.2.4 Capillary Retention

Capillary retention makes for a completely passive system. However, the capillary system does not have the high power requirements of the dielectrophoretic system. The primary experience with capillary systems has been with small engine liquid propellant start tanks, and they have not been tested for continuous liquid transfer. This method is adversely influenced by heat leaks through the capillary structure, which can cause vapor formation within the capillary structure which can alter liquid/gas equilibrium configurations. Such a system is limited to low levels of external acceleration.

A.3 PRESSURIZATION

Two methods of tank pressurization were considered: (i) external inert gas pressurization using stored helium gas; and (ii) liquid/vapor conversion. Although the stored gas pressurization system was lighter for the oxygen tank, this method was rejected as the result of technical reviews at NASA and liquid/gas conversion was used for both tanks. In this method, liquid is bled from each of the tanks, pressurized and vaporized, and reintroduced into the ullage section of each tank. The pressurant gas requirement is based on the thermodynamic properties of the fluids and the bulk density of the liquid expulsed. Both oxygen and hydrogen tanks require liquid/gas conversion equipment. Table A-3 summarizes the advantages and disadvantages of the two systems.

A.4 PROPELLANT TRANSFER

Three modes of propellant transfer were considered: pump transfer, positive displacement, and direct pressure. In the pump transfer subsystem, a pump is used to provide the necessary head to transfer the propellant from the donor tank to the recipient tank. In this method, propellant is introduced to the pump with the necessary net positive suction head (NPSH). The pump provides the necessary work to transfer the propellant into the recipient tank at the required temperature and pressure. In the positive displacement method, a positive displacement device, either a bladder or a piston, is used to expulse propellant out of the donor tank into the recipient tank. No pumps are used in this system. In the direct pressure system, the ullage above the liquid is pressurized so as to provide the required NPSH to push the liquid into the recipient tank. In this method, the propellant is effectively expulsed from the donor tank into the recipient tank.

Table A-3. Comparison of Pressurization Systems

Method	Major Advantages	Major Disadvantages
External Pressurization (stored GHe)	1. May be used for pressurizing both propellants 2. May also be used for pressurizing other storables 3. Proven technique	1. Requires additional high pressure tank 2. Requires gas generator to provide heat
Self-Pressurization (liquid-gas conversion)	1. Utilizes ullage 2. Relatively low pressure system	1. Requires reaction chamber 2. Requires separate liquid/gas conversion equipment for each propellant

Table A-4 presents the major advantages and disadvantages associated with the three transfer methods. Pump transfer does not require a high pressure and results in a low residual gas weight. Pumping also provides the best method of controlling the propellant transfer rate. A disadvantage of this system is that a pressure source and a phase control are required for the entire duration of propellant transfer. In the positive displacement method, no ullage control is required. This is the lightest method for oxygen transfer. However, a bladder or piston is required in this system with the mechanism necessary to expulse the fluid. The applicability of bladders for tanks of this size is currently questionable. The direct pressure method requires the fewest moving parts and the propellant is effectively expulsed from one tank to another. High ullage pressures are required in this system; consequently, there is a high residual gas weight associated with this method. Since propellant transfer rate is limited by the ullage pressure, the transfer rate will be constrained by the structural design of the tank.

A.5 BASELINE SYSTEM SELECTION

Based on the cursory review and evaluation of the three major subsystems required for a propellant flow transfer system, the linear acceleration method was selected for phase control; pump transfer was selected for propellant transfer; and liquid/gas conversion was selected for the pressurization method. Although there currently is much debate over the merits of the linear acceleration method as against those of the rotational acceleration method, linear acceleration was selected in this study because of the relatively uncomplex nature of the method and because this method precludes the requirement of rotating joints, seals, and gimbals. The pump transfer method was selected because it is considered that this method provides the best control of propellant flowrate. Liquid/gas conversion was selected because of the NASA requirement to maintain only these two propellants on the station (i.e., no helium stored in the OPD).

Table A-4. Comparison of Pressurization Systems

Method	Major Advantages	Major Disadvantages
Pump transfer	1. Low ullage pressure requirement 2. Low residual gas weight 3. Ullage gas pressure equal to initial storage pressure 4. Lightest for H_2	1. Pressurant source required 2. Ullage control required for duration of propellant transfer
Positive displacement	1. No ullage control required 2. Lightest for O_2 transfer	1. Pressurant source required 2. Liquid/gas interface increases 3. Heaviest for H_2
Direct pressure	1. Fewest moving parts	1. Pressurant source and ullage control required 2. High ullage pressure 3. High residual gas weight 4. Pressurant gas condensation 5. Heaviest for O_2 ($t < 5$ hr)
In vitro	1. No propellant flow 2. Minimum time transfer 3. Flexibility of Direct Resupply OV to OPD transfer	1. Complete utilization of usable propellants not probable 2. Requires complex plumbing design

APPENDIX B

Docking Mechanism and Interface Mating Configurations

APPENDIX B

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FIGURES

APPENDIX B

DOCKING MECHANISM AND INTERFACE MATING CONFIGURATIONS

B.1 GENERAL

This appendix contains a discussion of the docking mechanism and interface mating configurations considered in the hazards analysis.

The docking mechanism is essentially the same for all OPD concepts, differing only in details of operation. The mechanism consists primarily of a universal docking adapter and locking latches.

The resupply and dispensing fluid and electrical interfaces are the same for both the integral and semimodular concepts. The same interface configuration is also utilized in the modular concept when a propellant tank is transferred to the user OV.

B.2 DOCKING CONFIGURATION

B.2.1 Integral and Semimodular Concepts

The docking sequence for the integral and semimodular concepts is shown in Figure B-1. During the OPD's quiescent mode of operation, the docking mechanism is retracted into a protective housing which also contains the propellant transfer interface connectors.

When a resupply OV or user OV is to dock with the OPD, the mechanism is actuated to the extended position. In this position, the mechanism projects beyond the transfer interface connectors, minimizing the likelihood of their being damaged by the docking operation. With the OV secured to the OPD, the docking mechanism is retracted into its housing, drawing the OV into position for the interface connectors to be mated. The process is reversed to separate the OV from the OPD.

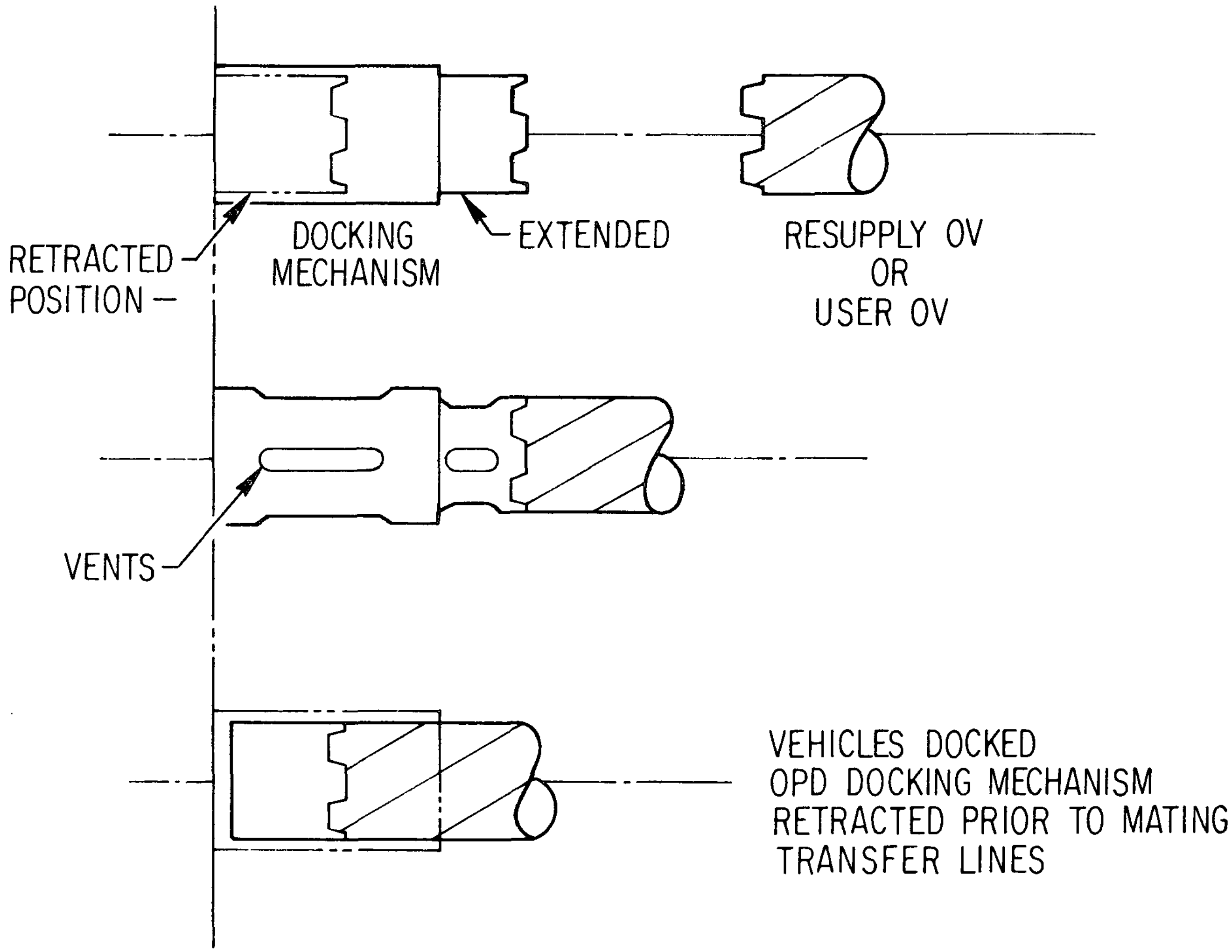

Figure B-1. Docking Configurations, Integral and Semimodular Concepts

B.2.2 Modular Concept

The docking configuration established for the modular concept is presented in Figure B-2. This configuration differs from that described for the integral and semimodular concepts in that the docking mechanism located on the OPD is fixed, since it need not extend to protect any interface connectors.

It will be noted that the propellant tanks used in this concept have docking adapters on both ends. The adapter on the tank end that mates with the user vehicle houses the interface connectors. The docking adapter on the user vehicle is identical in configuration and operation to that described in paragraph B.2.1, extending for the docking sequence and retracting to position the transfer interface connectors for mating.

B.3 INTERFACE MATING

B.3.1 Integral and Semimodular Concepts

There are two interface mating concepts associated with these OPD configurations; one for resupply of the OPD, the other for servicing a user OV. It is recommended that the structure surrounding the interface be vented to prevent pocketing of propellant gases that could result in possible fire explosion. The ability to purge this area from the user OV helium tanks appears desirable.

B.3.1.1 OPD Resupply

During resupply operations, a propellant module is attached to the OPD docking mechanism by the resupply OV which then stands off a safe distance and commands retraction of the docking mechanism. The retraction cycle automatically engages the fluid, pressurant, and electrical connectors necessary for propellant transfer (Figure B-3). The cycle is reversed to allow the resupply OV to recover the propellant module from the OPD when the transfer is complete.

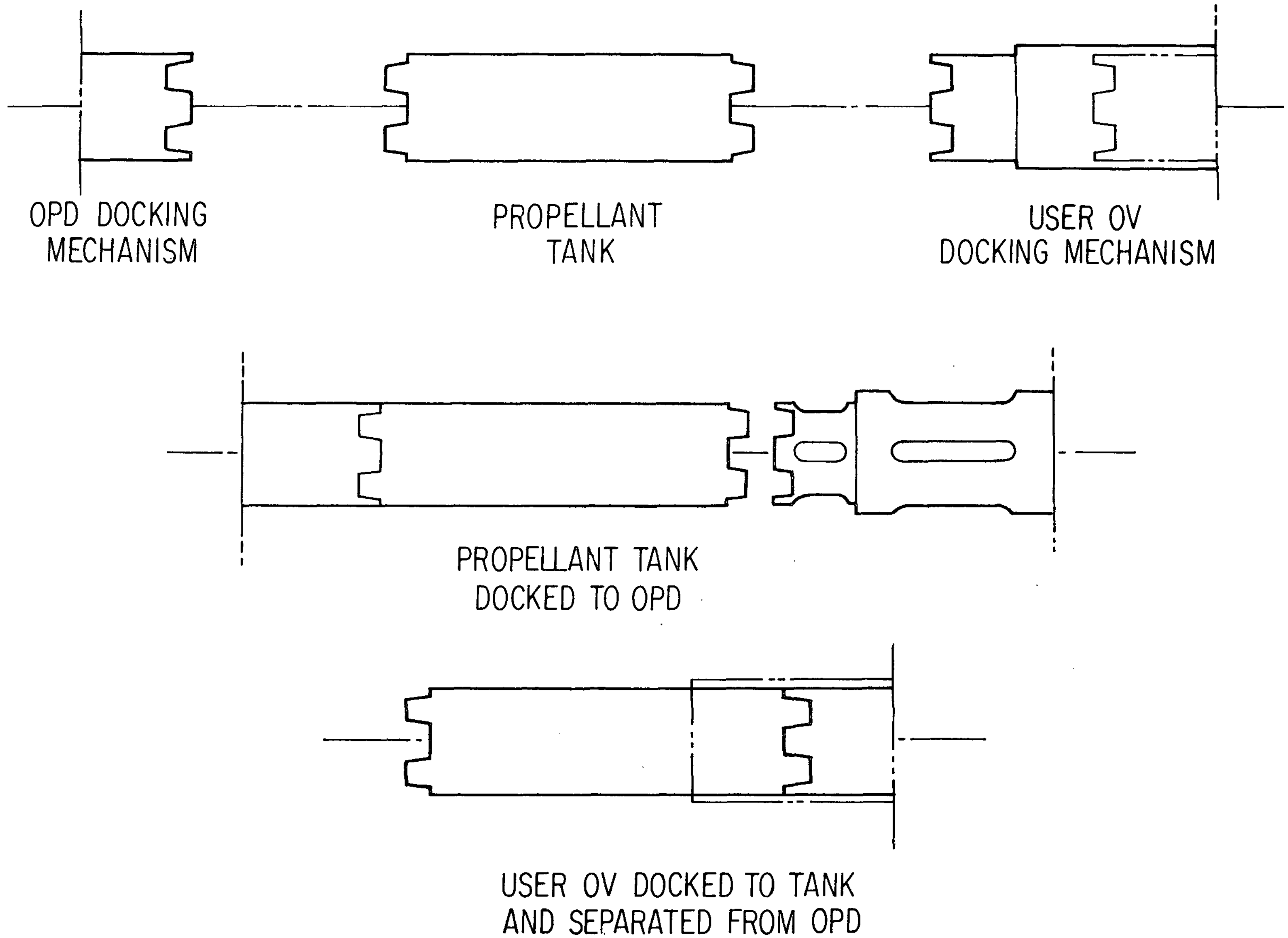

Figure B-2. Docking Configuration, Modular Concept

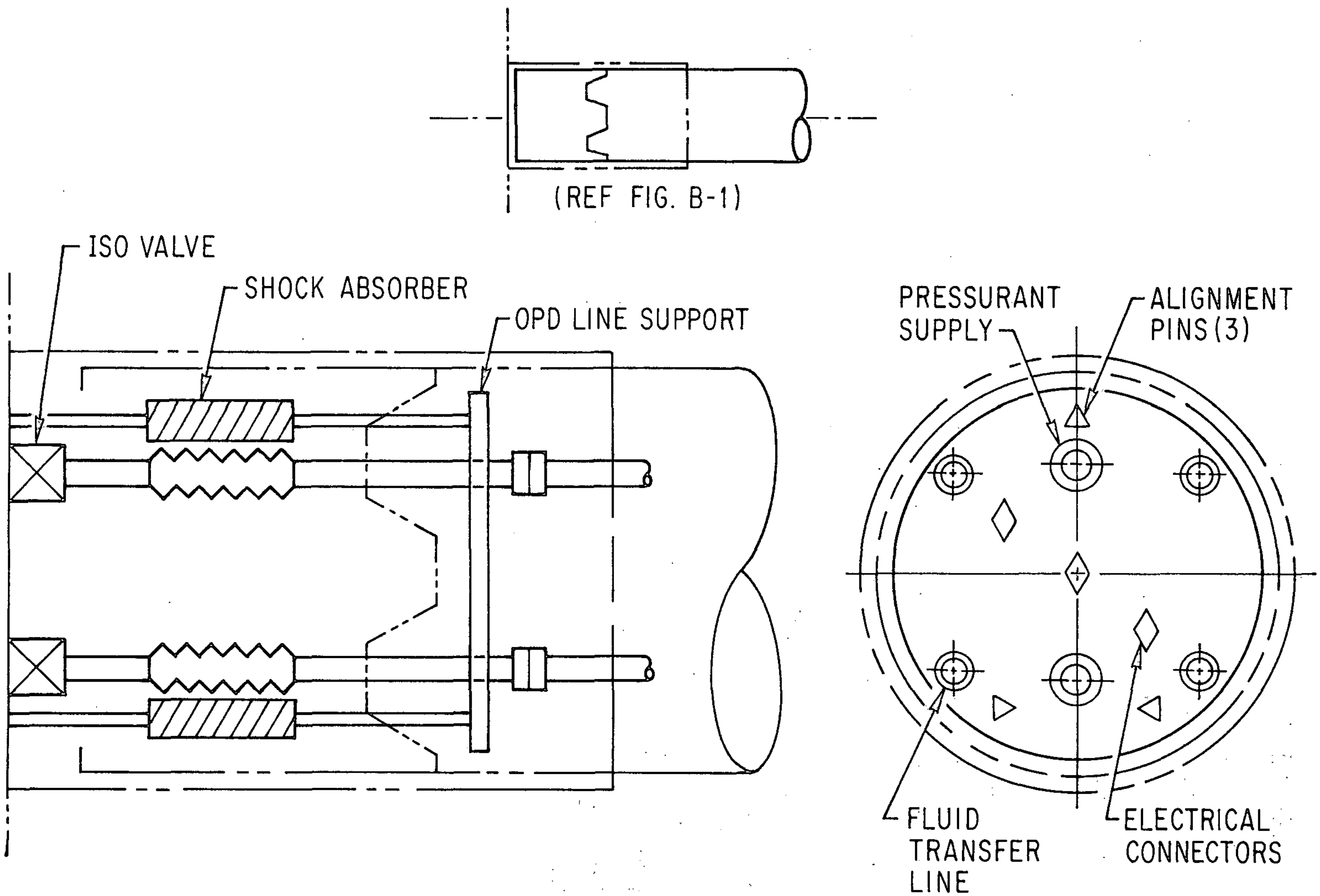

Figure B-3. OPD Resupply, Interface Connector Mating Configuration, Integral and Semimodular Concepts

B.3.1.2 User OV Resupply Configuration

Interface mating for user OV resupply operations is similar to that described for OPD resupply operations, except that the interface connectors are not automatically mated when the docking mechanism is retracted. In this case, the retraction operation only positions the connectors for mating.

Mating of the interface connectors is controlled by the user OV. Hydraulic or electrical actuators (Figure B-4) allow each connector to be extended for mating. When connection is made, a leak check system utilizing the user OV's helium pressure supply is activated to check the integrity of the connections prior to initiating propellant flow. Redundant fluid transfer connectors are provided in the event that a transfer connector malfunctions. To terminate the propellant transfer and separate the user OV from the OPD, these procedures are conducted in reverse order.

B.3.2 Modular Concept

When a propellant tank is transferred, the interface connectors are mated and pressure tested in the same manner as described in paragraph B.3.1.2, except that the retraction of the docking adapter prior to mating occurs on the user OV side of the interface (Fig. B-2).

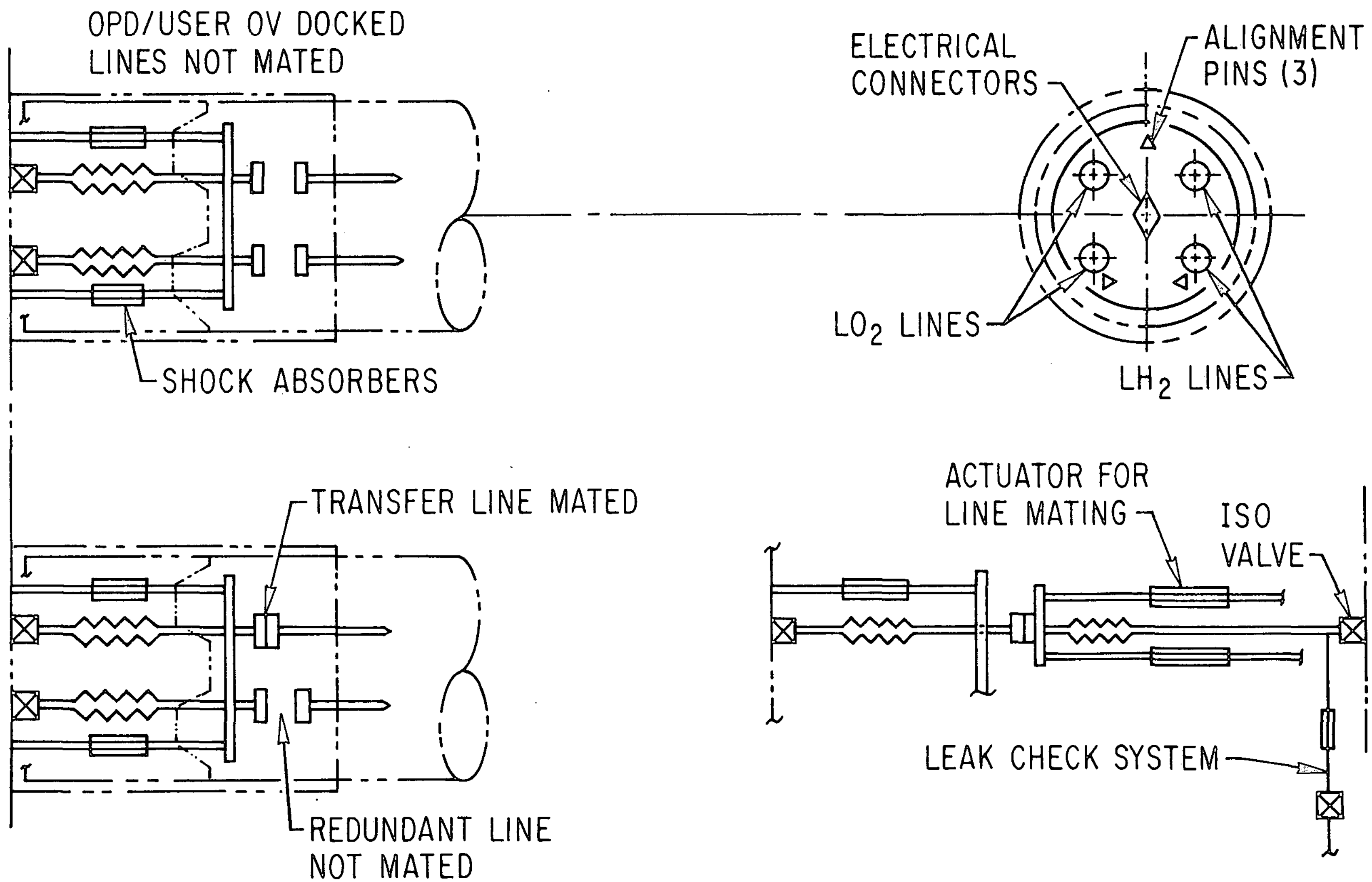

Figure B-4. **User OV Resupply, Interface Connector Mating Configuration, All OPD Concepts**

APPENDIX C

Hazard Categories

APPENDIX C

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APPENDIX C

NASA HAZARD CATEGORIES

C.1 GENERAL

The NASA hazard categories noted below were used in the hazard analysis reported in this study. They were obtained from the Office of Manned Space Flight, Program Directive M-D-MT-1700.120, dated 12 December 1969, and are repeated here for the convenience of the reader.

C.2 SAFETY CATASTROPHIC

Condition(s) such that environment, personnel error, design characteristics, procedural deficiencies, and/or subsystem or component malfunction(s) will severely degrade system performance(s) and might cause subsequent system loss, death, or multiple injuries to personnel.

C.3 SAFETY CRITICAL

Condition(s) such that environment, personnel error, design characteristics, procedural deficiencies, and/or subsystem or component malfunction(s) might cause equipment damage or personnel injury, or result in hazard(s) requiring immediate corrective action for personnel and/or system survival.

C.4 SAFETY MARGINAL

Condition(s) such that environment, personnel error, design characteristics, procedural deficiencies, subsystem failure(s), and/or component malfunction(s) might degrade system performance but could be counteracted or controlled without major system damage or injury to personnel.

C.5 SAFETY NEGLIGIBLE

Condition(s) such that personnel error, design characteristics, procedural deficiencies, subsystem failure(s) and/or component malfunction(s) might not result in major system degradation and would not produce system functional damage or personnel injury.

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